HIGH TEMPERATURE BEARING AND DRY - LUBRICATION CONCEPTS

PHASE I

FINAL REPORT

VOLUME II

SEPTEMBER, 1982

August O. Weilbach

Sponsored by:

Defense Advanced Research Projects Agency (DoD)
DARPA Order No. 4477/1-8-82
Monitored by Office of Naval Research
under
Contract N00014-82-C-0248

Submitted by:

Mindrum Precision Products
Rancho Cucamonga, CA 91730

Helvart Associates
Fullerton, CA 92635

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER MPP-82-1027 Vol.II	2. GOVT ACCESSION NO. AD-A122542	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) HIGH TEMPERATURE BEARING AND DRY-LUBRICATION CONCEPTS		5. TYPE OF REPORT & PERIOD COVERED Addendum to Final Report September 1982
		6. PERFORMING ORG. REPORT NUMBER MPP-82-1027
7. AUTHOR(s) A.O. Weilbach		8. CONTRACT OR GRANT NUMBER(s) N00014-82-C-0248,
9. PERFORMING ORGANIZATION NAME AND ADDRESS Mindrum Precision Products 10,000 4th Street Rancho Cucamonga, CA. 91730		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Department of the Navy 800 North Quicy Street Arlington, Virginia 22217		12. REPORT DATE September 1982
		13. NUMBER OF PAGES 21
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE
DISTRIBUTION U[illegible]

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Ceramic Bearings, Solid Lubricants, High Temperature Lubricants, Lubricant Test Methods, Lubricant Replenishment, Wear Tests, Ball Retainers.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Ceramic Bearings, Solid Lubricants, High Temperature Lubricants, Lubricant Test-Methods, Lubricant Replenishment, Wear Tests, Ball Retainers.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Test-log records are reduced to readily understandable data showing the conditions the solid lubricants and the test-bed bearing were subjected to. Illustrations describe the test-rig and indicate bearing material defects and present views of surfaces with and without lubricant coating.

DD FORM 1473 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

HIGH TEMPERATURE BEARING AND DRY - LUBRICATION CONCEPTS

PHASE I

FINAL REPORT

VOLUME II

SEPTEMBER, 1982

August O. Weilbach

Sponsored by:

Defense Advanced Research Projects Agency (DoD)
DARPA Order No. 4477/1-8-82
Monitored by Office of Naval Research
under
Contract N00014-82-C-0248

Submitted by:

Mindrum Precision Products
Rancho Cucamonga, CA 91730

Helvart Associates
Fullerton, CA 92635

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS AND TABLES

1.0 Introduction

This volume presents a detailed extension to the test summary contained in Appendix A of the final report (See page 54). In addition it provides information on additional work done since the end of the study program. It also shows actual photographs of the test-rig (Fig. 1), the test-bed bearing and differences in lubricated and unlubricated surfaces (Fig. 3

The test-log has been reduced to easily understandable data showing the different conditions the bearing and the dry lubricant were subjected to.

In the interim period and before the start of this writing, the Mindrum/Helvart team achieved a mile-stone by actually testing one of the solid lubricant formulations within the test-bed bearing at a temperature of 820 deg. C and while rotating at 2000 rpm.

Included also are notes on the usage and behavior of two types of ball retainer materials.

2.0 Solid lubricant performance

2.1 Formulation Characteristics.

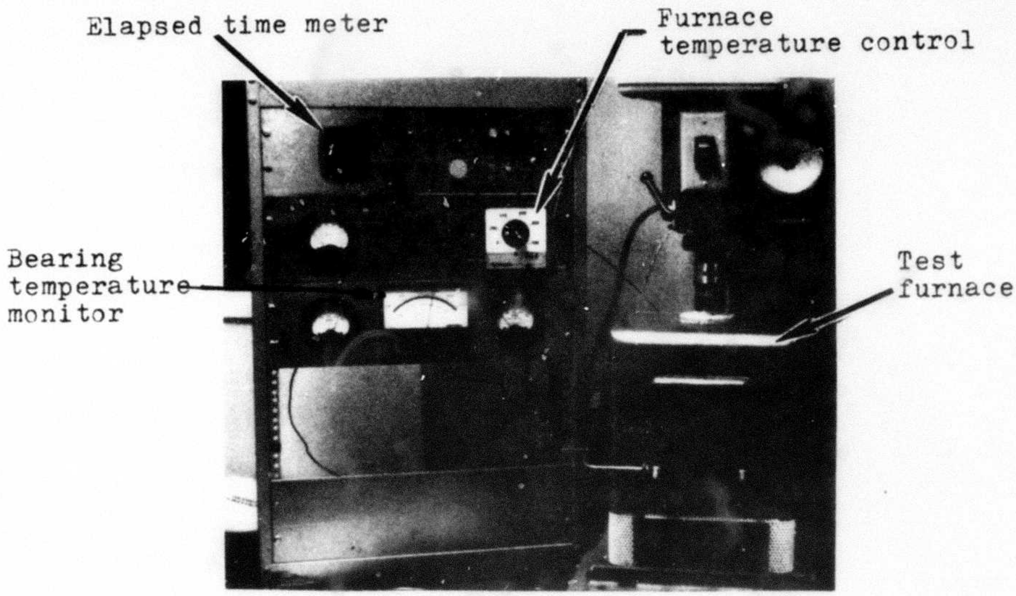
Testing continued after the release of Volume 1 of the final report provided a possibility to re-check previous data to verify previous results. Based on this follow-up work some corrections concerning previous information about the solid lubricant formulations are in order.

It was established that only freshly prepared formulation of 2-14-SI enabled us to arrive at the 800 deg. C level under running condition. At that level the Silver had pretty much disappeared but further observation of the formulation gave indications that the additives, through amalgamation (see footnote 1) or similar process had faded into the mix without being detectable under the microscope.

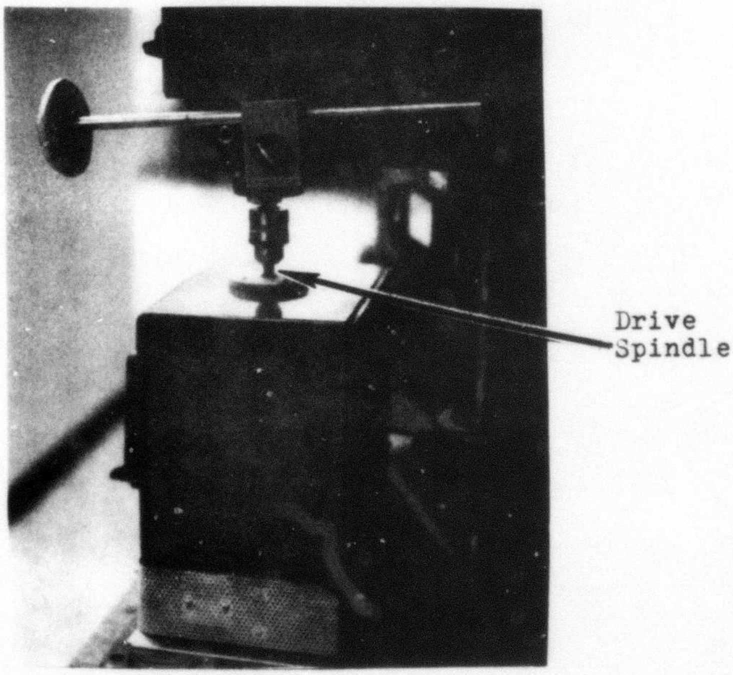
----

1. No Mercury or mercury treatment is used in the formulation but the basic material constituents have at this time not been tested for its possible mercury contamination.

Figure 1. Test-rig with detail of bearing pre-load system



Calibrated pre-load mechanism



In contrast though formulation 2-14-I, during the final high temperature test, survived a 820 deg. C level without indication of deterioration.

2.2 Run-in Cycles

The summary in Appendix A mentioned the difficulties encountered in the application of a precious metal coating (Silver) on to the Silicon Nitride substrate material. To this point we have been unsuccessful in creating a reliable bond, and in order to proceed with the testing of the various formulations, had to find a temporary solution to bond the solid lubricants to the substrate. In reviewing results of formulation adhesion it was evident that the method of the run-in cycle had different effects in forming a good bond.

Bake-out cycle at approximately 250 deg. C eliminated "lumping" of the finely dispersed lubricant particles. This in all probability is due to elimination of excess moisture absorbed and adsorbed by the particles. A subsequent 5 - 6 minute run-in under minimal load will create a firm and smooth film that will provide an adhesive base for relubrication. Further tests after changing the proportions of the "neutral" additives as described in section 3.5.2, p. 30, Vol 1, allowed further optimization of bonding quality. Running the bearing at higher temperature and slightly increased loads resulted in the forming of a very uniform well wearing film that is removable only with a 30% Nitric Acid solution. The film reduces the time cycle for relubrication. Excessive relubrication will result in increased bearing noise and starting torque.

2.3 Effects of relubrication

It was interesting to observe that the higher the temperature, the less the need for frequent relubrication. We feel it is premature to arrive at firm conclusions, since much depends on thrust load, bearing speed and the type of formulation applied. However, the observed results do indicate this trend starting at temperatures of 250 deg.C. The inconvenience of handling the bearing at high temperatures prompted the decision to relubricate at 500 deg.C once only, then conditions permitting, to go on the the 800 deg. C level. At each interval of 100 deg. the oven and the test article were stabilized in static condition and with the bearing preload removed. The relubrication provided a film build up beyond what was expected and resulted in a quieter run and in a clean and extremely tenacious film. See Section 3.2 and Figure 3

Numerous tests were conducted at various speeds and loads and at temperatures below 250 deg. C. See detail in section 2.4. Given enough time and load the film will eventually wear down to a layer thin enough to show interference colors and relubrication must be applied before film break through. Over-lubrication on the other hand will result in bumpiness and generation of excess debris. Optimized thickness levels have to be established through further testing and analysis.

Using the various formulations also gave firm indication that, the finer the dispersion, the smoother the surface and the shorter the requirement for run-in of the assembled bearing.

As pointed out in section 3.5.2 of Volume 1, the most effective and desirable way to apply the first solid lubricant coat will be by sputtering or similar procedure.

Figure 2. Upper Race showing material and coating defects

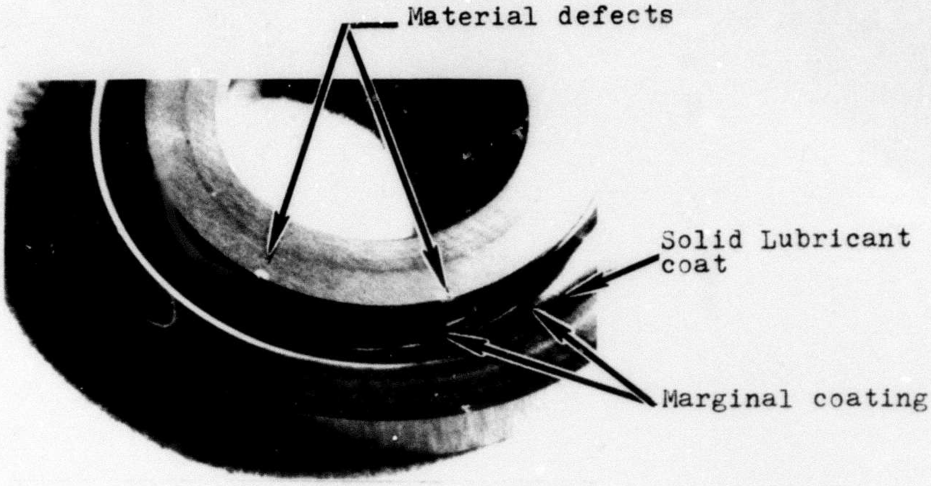
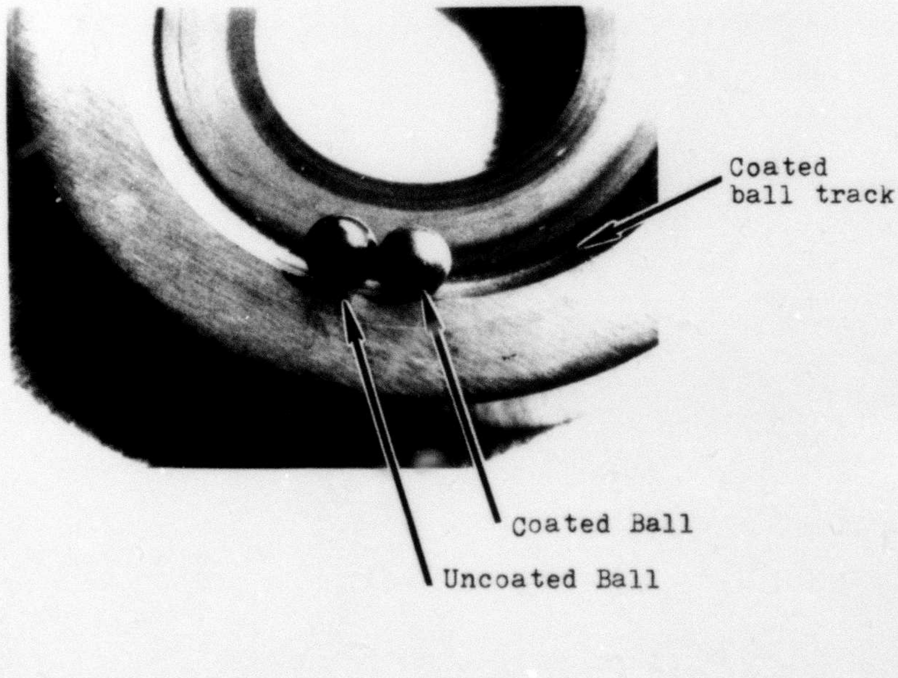


Figure 3. Lower race showing coating and coated and uncoated balls



2.4 Test Log Summary

The test-log summary presents all significant data reduced into a meaningful record of the test performed with the test-bed bearing and most solid lubricant formulations. Figure 4 shows a page from the original test-log. Subsequent pages represent the reduced data. Further condensed from this information are the following highlights:

* Total test-bed bearing revolutions	1,822,600
* Maximum bearing speed	1950 rpm
* Maximum thrust load	25 kg
* Minimum thrust load	2 kg
* Minimum starting Torque	.008 grm/cm
* Maximum starting torque	.12 gm/cm
* Maximum running temperature	820 deg. C
* Average time between re-lubrication	18 minutes
* Maximum time without re-lubrication	1 hr. 12 minutes
* Best performing formulation	2-14-I

Detail information on the test bearing is presented in Volume 1, section 4.3.3 and Figure 1, page 5; figure 18, page 41.
Dimensions are given on page 79.

3.0 Test-Bed Bearing performance

3.1 Stability and Surface Finishes.

One of the outstanding characteristics of the Silicon Nitride used to manufacture the test-bed bearing is that it maintained dimensional stability for over 30 hours of running time under Hertzian stress loads of over 280 ksi and at temperatures reaching over 820 deg. C. At one point during the start-out of the test cycle the bearing races went though an annealing cycle at 1000 deg. C. This operation was performed in order to assure that no residual surface stresses introduced during the final polishing cycle would have a detrimental effect during the early runs of the test-bearing. Such stresses could possibly result in microcrack initiation or propagation. Figures 2 and 3 show clear evidence of material

9 Cont Running 9-9-82 - 9-10-82 for Repeatability

DATE	RUNNING TIME START	RUNNING TIME STOP	TOTAL HRS	TOTAL MIN	TEMPERATURE OVEN	TEMPERATURE RACE	LOAD Kg	SPEED RPM	LINEAR SPEED METERS/SEC.	STARTING TORQUE gm/cm	LUBRICANT FORMULA	LUBRICANT SYSTEM	LUBRICANT REPLENISHING	COMMENTS
9-14-82	52.3				25	26.6	33Kg	780	2.213		2-155I		✓	typ Race only (Very lite)
		52.55		05	25	26.6								
		52.8	1	00	25	26.6			23400					
	52.8						33Kg	1300	3.708	.075				
		53.05		15	✓	✓								Running Very quiet
		53.3		30										
	53.3										2-155I	Brushing	✓	Good coat on ball path not exactly like B-[illegible]
		53.55		45										
		53.8	1	00			33Kg	1300	3.708 [illegible]	.075				
9-15-82	53.8				24°	24°	11Kg	1950	5.562 meter/sec	.08	2-155I			washed clean except [illegible] deposit on balltrack
		53.85		3	24	26.6°								
		53.9		6	24	29.4°	11Kg						✓	
		53.95		9	24	32.2°	33Kg							
		54.0		12	25	32.2°					2-155I		✓	inspection - ok
		54.3		30	25	32.2°C	33Kg	1950	5.562 meter/sec 535100	.07				good [illegible] - Spreading & thinner, + film
using phenolic retainer														
9-16-82	54.3				24.4°	24°	11Kg	470	1.333 meter/sec	.09	2-44I	Brushing	light coating with Brush	
		54.55		15	✓	26.6°							✓ upper [illegible]	- Scattered buildup & metallic particles and thin film -
		54.8		30	✓	27°				.11				- noisy after Lube
	54.8													quite Running
		55.05		45	✓	29°		470	1.333 19740				[illegible]	- scattered metal - good thin film, [illegible]
		55.3	1	00	25°	30.5°	11Kg	780	2.213 [illegible]					

Figure 4. Sample page of test-log

Bearing Speed rpm	Thrust Load kg	Temp. deg. C	Testing Time hrs min	Solid-Lubricant Formula	Starting Torque gm/cm	Re-Lub Supplied yes	Re-Lub Supplied no	Comments
	0.2 (A)			none	0.025			(A) constant for all torque tests
470	2.5	25	18	2-14	0.1 S 0.075E		*	S Start of test E End of test
470	2.5	25	1 00	2-14	0.05 E	*		
470	7	25	2 24	2-14		*		Periodic inspection of lub coat.
470	11.5	25	2 6	2-14	0.080E	*		increased bearing noise for 15 min. Normal for balance
470	16	25	48	2-14	0.05		*	Low bearing noise. Track inspection showed interference colors.
470	2.5	25	18	2-14-SI	0.12 S		*	Noisy
470	7	25	24	2-14-SI		*		Noise reduced
470	11.5	25	30	2-14-SI	0.075E		*	Further noise reduction
780	2.5	25	18	2-14-SI		*		Small noise increase after relubrication
780	7	25	2 24	2-14-SI	0.05 E	*		Small silver streaks on balls and tracks
780	11.5	25	18	2-14-SI			*	

Bearing Speed rpm	Thrust Load kg	Temp. deg.C	Testing Time hrs	min	Solid-Lubricant Formula	Starting Torque gm/cm	Re-Lub Supplied yes	no	Comments
780	16	25		18	2-14-SI	0.08 S	*		Balls cleaned of all residual lubricant
780	16	25	1	00	2-14-SI	0.05 E	*		Reduced adhesion of solid lubricant Color brownish
1300	11.5	25	1	12	2-14-S	0.085 S		*	Fully cleaned bearing. New Formulation
1300	16	25	1	12	2-14-S	0.05 E	*		Lubricant color brownish. Variable bearing noise.
1300	25	100		30	2-14-S		*		Re-lubricated with 2-14
1300	25	150	1	12	2-14-S	0.075	*		Quiet run but further lubricant deterioration No evidence of residual Silver
1950	11	25		18	2-14-SB	0.10		*	Fully cleaned bearing Formulation with Aluminum Phosphate(B) as a bonding additive
1950	16	150	1	12	2-14-SB		*		Medium bearing noise
1950	25	250		54	2-14-SB	0.10	*		Increased noise Good bond but rough surface on balls and races.

Bearing Speed rpm	Thrust Load kg	Temp. deg.C	Testing Time hrs min	Solid Lubricant Formula	Starting Torque gm/cm	Re-Lub Supplied yes	Re-Lub Supplied no	Comments
1950	7	100	1 42	3-14	0.08	*		Medium bearing noise
1950	7	175	42	3-14	0.075		*	Low noise. Poor lubricant bond
1950	16	25	24	2-14-I	0.075		*	Fully cleaned bearing New Lubricant
1950	16	250	24	2-14-I			*	Low noise Even lubricant distribution
1950	16	25	30	2-14-I	0.075	*		Very low noise Smooth lubricant distribution
1950	11	250	12	2-14-I	0.050		*	Lub film shows interference colors
1950	11	400	12	2-14-I				Very lowbearing noise
	0	(500)	(45)			*		Re-lubrication before stabilizing
1950	7	500	12	2-14-I			*	Low bearing noise
	0	(600)	(45)					Temp. stabilization
1950	7	600	6	2-14-I			*	Very low bearing noise
	0	(700	(45)					Temp.stabilization
1950	7	700	12	2-14-I			*	Low bearing noise
	0	(820)	(50)					Temp. stabilization
1950	7	820	12	2-14-I	0.075 △1		*	Slightly increased noise

( ) Values in parenthesis represent stabilization time and temperature.

△1 Torque as measured after cool-down.

defects that slowly appeared during bea.ing usage. The first indication of such defects (pores or Inclusions) started to show after Ion-beam cleaning of the bearing races. It is interesting to note that on the coated race track (see figure 2, are two areas that only reluctantly provide a bond to the generally excellent adhesion of the solid lubricant. One could assume this to be a concentration or the lack of Yttria, the material used to stabilize the Silicon Nitride during the sintering or hot press operation.

The balls made of Norton NC 132 appear much the same after the severe exposure of pre-loaded running at both ambient and high temperatures. One must realize that for each revolution of the race the balls rotate approximately 25 times. With over 1.9 million bearing revolutions achieved during the test, the 3/16 inch diameter balls have rotated over 47.5 million times.

3.2 Cleaning methods.

In order to evaluate the different formulations under different running conditions it was necessary to periodically clean the bearing components of the solid-lubricant deposit. To assure that all Silver (present in some of the formulations) would be completely removed, a 30% Nitric acid solution was used as the standard cleaning agent. It became obvious that the length of time required for removal of the layer became a measure of adhesion of the lubricant to the substrate. In between removal of excess and loose lubricant was achieved with alcohol impregnated Q-Tips. There is no evidence that the use of alcohol had any effect of the lubricant quality.

The ball retainers were cleaned simply and wiped dry of excess material. It was observed that after reaching the 500 deg. C test levels, the Nitric acid solution proved to be useless for removal of the lubricant. A better solvent is being searched for. Since Silicon Nitride is attacked in concentrated hydrofluoric acid it cannot be used as a solvent for the lubricants.

3.3 Bearing design recommendations

Despite the outstanding performance of the test-bed bearing it became obvious, during the study and the extended testing, that a bearing with larger diameter balls and with a greater number of balls would be desirable. Without having to change any of the bearing outside dimensions, ten, rather eight balls of 6mm diameter could be accommodated. There are some questions as to the best contact angle and to the conformity ratio for this type of bearing. For final use other bearing configurations have to be considered. This aspect is discussed in section 6.0 of this volume. The quality of the material to

be used for any ceramic bearing needs to be analyzed the best possible way before proceeding to final grinding and polishing.

4.0 Ball Retainer Varieties and Characteristics

4.1 Polyimide Retainers

Polyimide plastics were used both for ambient temperature testing and at temperatures up to 250 degrees C. The material VESPEL tm SP 1 grade is ideal for such an application and indeed performed very well. It can be easily machined into a relatively complex shape. It has excellent physical properties including resistance to relatively high temperatures. Its frictional properties are adequate for such tests and it will resist wear and abrasion much more so than phenolic retainers.

4.2 Boron Nitride

Hot pressed Boron Nitride materials are available from several manufacturers and in several different compositions and qualities. Properties such as yield and rupture strength are substantially below the Polyimides. Its resistance to high temperatures, however, is excellent as is the low friction quality. Several machinable grades are available and thus in the overall the boron Nitride proved to be a very useful choice for our application. The part as shown in Figure 5 did an excellent job at all temperatures and at the moderate speed of 2000 rpm. Certain care has to be taken during the machining and cleaning process but once accustomed to it, no special problems are apparent. After the machining operation it is advisable to bake out the part at roughly the highest temperature the retainer will be exposed to during its working cycle.

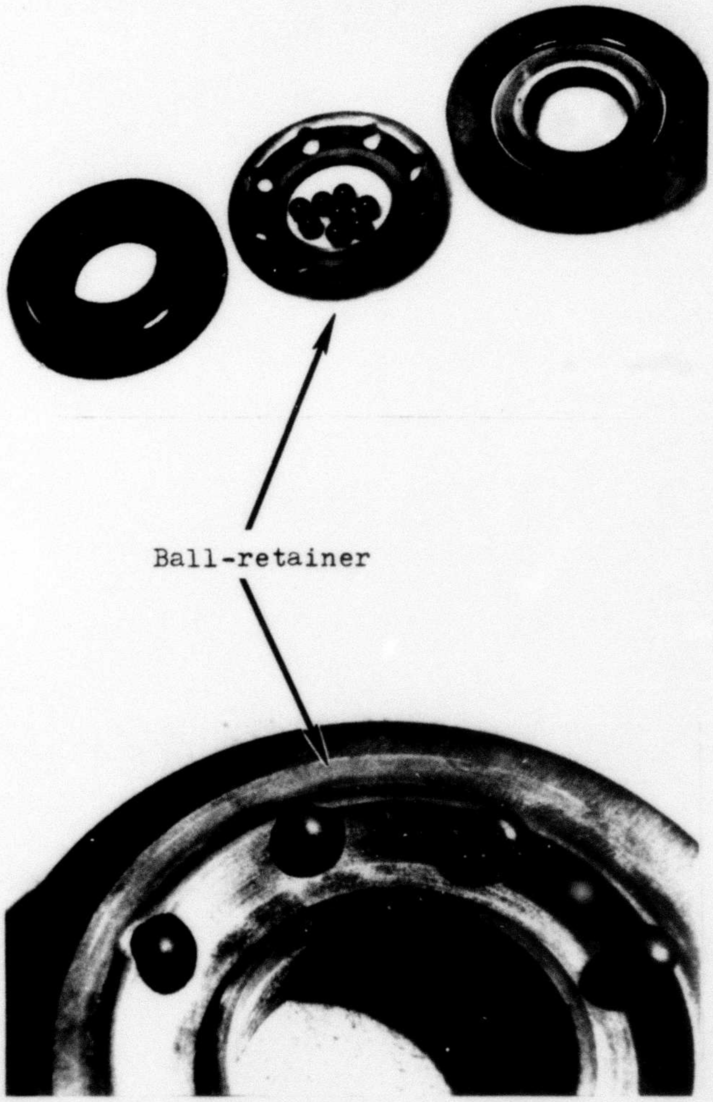
4.3 Limitations of tested materials.

As mentioned in the two previous sections material selected and tested during the course of this study, have limitations with regards to strength and temperature. In either case the retainer materials must not be considered as the primary source of lubrication unless the life of the bearing is short termed and/or running at relatively low speeds and loads. For unlubricated high precision ceramic bearings running at temperatures from -50 to +150 deg. C, polyimides, such as VESPEL, are highly recommended. The retainer should be put through a carefully controlled preparation by setting up a

----

2. VESPEL is a trademark of the DuPont Company.

Figure 5. Bearing components and balls within retainer



run-in cycle to provide uniform conformity within the ball cavity. For high speed bearings running at elevated temperatures, reinforcements of the cage, along suggestions presented in section 2.5.3 of Volume 1, must be considered.

Obviously, the search for better retainer materials must go on. The ideal material will have light weight, high strength, be temperature resistant, and have low friction quality and good wearability.

5.0 Test Systems

5.1 Test System Modifications

For temperature testing two types of ovens were used. The oven shown in Figure 6 was mostly used in the early tests and medium temperature range (150 - 300 deg. C). The set up proved to be cumbersome in reaching set temperatures within a reasonable time period. The modified electric furnace shown in figures 1, 7 and 9 provided faster heat up, faster stabilization and better temperature control. The flap door provides ready access to the bearing. For either oven it was necessary to plumb the drive rod into a vertical position and to level the bearing support table in relation to the rod. A cushion of Silver powder provided a perfect match between the spherical drive-rod tip and the cavity in the top of the adaptor plate. The Silver at the same time provided some lubricity to cope with small oscillatory motions between the rod and the drive plate (Fig.). These motions resulted from residual misalignment between the two components.

Heat-leaks through the drive rod and up into the drive spindle stayed within acceptable levels and even at oven temperatures of 840 deg. C did not exceed 100 deg. C.

5.2 System Limitations

The most significant limitation of the test system is in the inability to reach high rpm values. It is for that reason that we suggested in section 4.2.3 of Volume 1 to take advantage of existing equipment that could be used with little modification and on short notice.

Another disadvantage of the present set-up is the inability of being able to check changes in torque values of the bearing. As previously pointed out, we have periodically measured starting torque at the beginning and at the end of cold and hot runs. These torque values still provide important information.

Figure 6. Round test-furnace

This figure is an actual photograph of the test-rig of the sketch in Figure 17,page 40,Vol.1

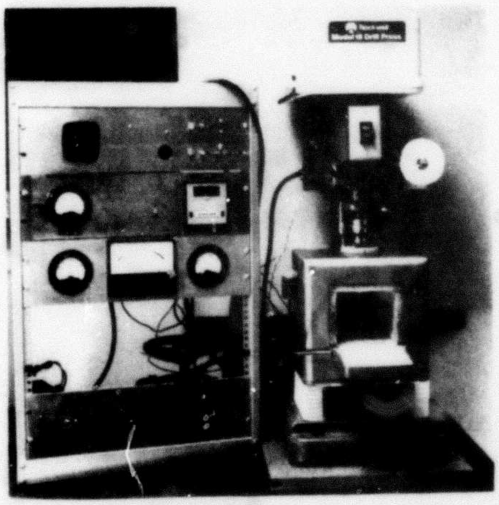
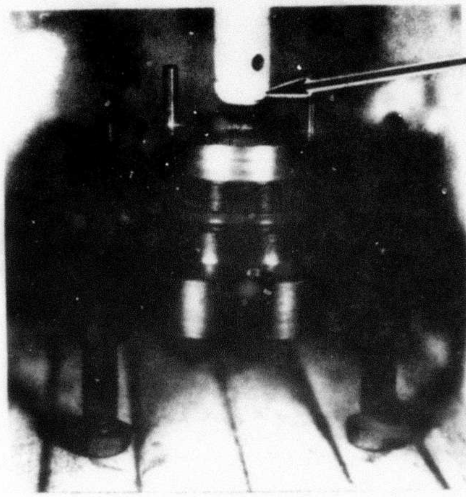


Figure 7. Test-rig with high temperature furnace

Figure 8. Bearing holder with Silver tipped drive-rod



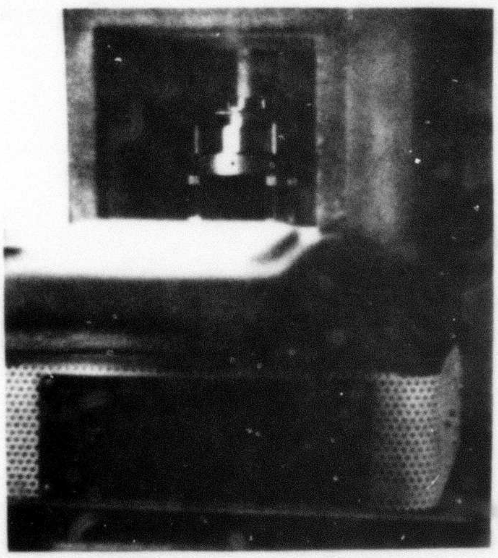


Figure 9. Bearing and bearing fixture in high temp.furnace.

The design of the test bearing puts undue strain on the retainer performance since the motion of the balls exert a thrust load onto one land of the retainer diameter and by this fact, increases the frictional load of the ball within the ball pocket.

Such condition will be greatly minimized by use of a regular angular contact or radial bearing. Despite this condition removal of material within the ball pocket was minimal, but still sufficient to run 500 - 850 deg. C tests without relubrication. Because of time and cost limitations, only one bearing was available to test the validity of the lubricating formulations. Further tests need to include several bearing configurations including roller type bearings. All indications are that the latter type will perform well and would resolve a number of problems associated with running a turbine main shaft bearing within or close to the hot section of the engine.

6.0 Technical recommendations

The main recommendations are presented in Section 6.0 of Volume 1, and are still valid in the light of additional work and the results of the high temperature tests. These very same tests, however, brought up additional facts and suggestions.

* Very little is understood of the mechanism that provides the bond between the solid lubricant formulations and the substrate. It would be of great value to study this in depth for it is unlikely that we have optimum bonding conditions and further improvements will be expected. It is also unlikely that adhesion to substrate materials other than Silicon Nitride will be identical quality.

* Due to accelerated oxidation at higher temperatures of 350 deg. C and over, Silver, as an additive will lose its effectiveness and needs to be replaced with a pure or alloyed metal that will sustain higher temperatures.

* One must emphasize the importance of thorough mixing and sizing of the lubricant constituents. Also eventual production of target materials, that will allow sputtering techniques for coating the races and possibly the balls, need to be explored.

* Techniques to study the coating of silicon nitride substrate materials with a tin film of Zirconium Oxide should be started in the near future. Zirconia has a lower coefficient of friction than Si N_2, has excellent wear characteristics and withstands temperatures in excess of 1500 deg. C. Its high specific weight in relation to Si N_2 makes it somewhat

unsuitable for high speed bearings, balls, or races. A combination of these materials could, however, provide the best of both.